Meson Acceleration and Handling

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Abstract: The fundamental engineering techniques, such as high electric field produced by rf systems or lasers, strong magnetic field produced by the MegaGauss techniques and the various methods for high-energy particle handling, have been promoted rapidly, and the fields have been improved drastically. Those techniques are expected to explore the new frontier by using elementary particles for industrial applications. One of the scenarios to accomplish the application trials by elongation of the short lifetime of mesons is described in this paper.

Keywords: Meson, Short-lived, Particle acceleration, High-energy particle, Pion, Kaon.

1. INTRODUCTION

The astronomic studies bring worthwhile scientific purposes especially to high-energy particle science and fundamental physics. The particles falling down to the earth from space have very high energy and bring us numerous information on galaxy structure, elementary particles, and fundamental field interactions. But the event happens rarely and the intensity is very low for rapid promotion of fundamental studies and industrial applications, although there is a case of muon tomogrammphy [1] to monitor the inside of large-scale structures. An artificial production of high-energy particles is required, for instance by high-energy particle accelerators [2], and various fundamental technologies related on the high-energy particle science have been promoted. One of the technologies is laser-electron-photon method [3]. It enables to produce photons, which have very short wavelength of 1 fm, equivalent to the size of the scale of the nucleons. It means to explore the possibility of direct monitoring of the structure inside a nucleon, so to write, motion of quarks, and to bring a better understanding of uncertainty principle in quantum mechanism. The photon production by using conventional synchrotron radiation has been also discussed. When the 250 GeV electrons would be produced in the future accelerator complex, for example, International Linear Collider (ILC) [4], or Super TRISTAN [5], photons with a super short wavelength can be produced by using the MegaGauss devices. The wavelength λ_c can be calculated (Table **1**.) by the following equations for Lienard-Wiechert potential:

$$P_{SR} = \frac{e^2 c^3}{6\pi\varepsilon_0}\frac{\beta^2\gamma^2 B^2}{U_0{}^2} \tag{1}$$

$$h\nu = P_{SR}\frac{L}{c\beta} = \frac{L}{4\pi\varepsilon_0}\frac{2e^2c^2}{3}\frac{\beta\gamma^2 B^2}{U_0{}^2} \sim \frac{3h}{4\pi}\gamma^2\frac{c^2 B}{U_0\beta}$$
$$\Rightarrow BL \sim \frac{9h\varepsilon_0 U_0}{2e^2\beta^2} \sim \frac{9h\varepsilon_0 U_0}{2e^2} \sim 0.526[Tm] \tag{2}$$

$$\lambda_c = \frac{4\pi\beta^2 U_0}{3c\gamma^2 B} \tag{3}$$

$$U_0 \equiv \frac{m_0 c^2}{e}; \gamma \equiv 1 + \frac{eK}{U_0}; \beta \equiv \sqrt{1 - 1/\gamma^2} \tag{4}$$

where P_{SR}, h, m_0, c, ε_0, B, L and e indicate the radiation power, the Planck constant, the invariant mass of electrons, the velocity of light, the permittivity, the external magnetic flux density and the length for electron bending and elementary charge, respectively.

Table 1: Wavelength Versus Bending Field

B (T)	*L* (mm)	λ_c (fm)
1	525.6	183.2
10	52.56	18.32
100	5.256	1.832
1,000	0.5256	0.1832

Equation (5) is a representative expression of the uncertainty principle and indicates the identity of fundamental elements.

$$\delta p \delta x \geq \frac{\hbar}{2} \tag{5}$$

This relation indicates the Plank constant gives the limitation of existence certainty δx and momentum δp of particles, and is obvious in the case using particles moving near light velocity. This equation is also used to develop a new technology of quantum communication [6], based on the probability treatment of the existence.

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It is also enough to describe the particles and fields by the state parameters, invariant mass, charge, spin, and so on, for the conventional fundamental physics, but it would be possible to confirm the accuracy by direct monitoring of the elementary particles recently, as mentioned above. The validity of the new monitoring method is expected to be more confidence by the other method.

The next stage to understand nucleons in an atomic nucleus is to define the quarks' states and motions. The nucleus is almost composed of protons and neutrons, which are all made of combination of three quarks. It is better to understand by using the different numbers of the combination of quarks, two or four. The meson, which is made of two quarks, is one of the candidates as a new probe. The lifetime of elementary particles are very short, except for electron, proton, photon, positron (almost stable) and neutron (886.7 s), which have been already used for industrial applications. The lifetime of meson is short of about 50 ns, however it is longer than that of other elementary particles, so the promotion of meson applications had not been progressed. But there is a possibility to be prolonged according to the relativistic effect by high-energy acceleration, and is useful for industrial applications. Various meson applications can be expected if the lifetime could be prolonged more than 1 μs.

It was so difficult to accelerate mesons because the mesons produced by the conventional methods are not directional, the kinetic energy distribution is very broad, and the production efficiency is very low. The discovery of superconducting phenomenon enables to produce magnetic flux density of 10 T and to gather the isotropic mesons to some extent, but it is still small value for post-acceleration by using radio frequency rf-devices. The utility efficiency of mesons is, therefore, very small, as less than 0.1 %, although even if such small efficiency is useful for investigations on fundamental physics.

The further strong field has been developed especially in the field of solid-state physics, so called as the MegaGauss method [7]. The long-pulse field of 100 T can be produced by a non-destructive magnet, and the impulse field around 1,000 T can be produced by the field concentration method, which has been developed recently. The MegaGauss techniques enable to focus the isotropic meson within the orifices of the rf-cavities, and the directional and long-lifetime mesons can be expected. The possibility to realize the production of directional mesons and long-lifetime mesons is discussed here. Mesons decay and produce muons and neutrinos, so the promotion of muon and neutrino applications can be expected, such as muon tomography, and neutrino telecommunication, which enables to send information fast because of the very light mass.

2. APPLICATION CANDIDATES OF MESONS

The lifetime of mesons is very short for practical applications (Table **2**). It is, moreover, limited for charged mesons, because there is only one method by using an electromagnetic field to control mesons. Although there is a method to control neutral particles by the interaction of an external field gradient to a particle's spin, but the changeable energy range by the conventional rf acceleration/deceleration is very small in the order of neV, and it would be less than 1 eV by the EW high-intensity laser technique [8] now under development. There are two candidates, charged pions and charged kaons, for the industrial applications, from the viewpoint of lifetime and the recent techniques including nearest future development projects. The next candidates are D particles and B particles with a lifetime of the order of 10 ps.

Table 2: Invariant mass and Lifetime of Mesons

Particle	m_0c^2 (MeV)	τ_{life} (ns)
Neutral pion, π^0	134.9766	8.4E-17 (s)
Charged pion, $\pi^{+/-}$	139.57018	26.033
Neutral η	547.75	5.1E-19 (s)
η^*	957.78	1E-21 (s)
Charm η	2,980.3	1E-23 (s)
Bottom η	9,390.9	(very short)
Charged $K^{+/-}$	493.677	12.384
Neutral K^0_s	497.648	0.090
Neutral K^0_L	497.648	51.8
Charged $D^{+/-}$	1,869.4	1.04 (ps)
Neutral D^0	1,864.6	0.4103 (ps)
Strange $D_s^{+/-}$	1,968.3	0.49 (ps)
Charged $B^{+/-}$	5,279	1.628 (ps)
Neutral B^0	5,279.5	1.53 (ps)
Strange B_s^0	5,366.3	1.47 (ps)
Charm $B_c^{+/-}$	6,277	0.46 (ps)
$\rho^{+/-}$, ρ^0	775.8	4.38E-24 (s)
Φ	1,019.456	1.55E-22 (s)
J/ϕ	3,096.916	7.23E-21 (s)
Y	9,460.3	1.24E-20 (s)

Charged pion can be produced easily, because of the lighter invariant mass, by hitting the primary high-energy particles, for example, protons and deuterons with kinetic energy of more than 300 MeV, into the pion production target. It is used as the muon source, which is one of the elementary particles with the longer lifetime of 2.2 μs and as the neutrino source, which are produced after pion decay, for the fundamental studies on physics. It does not become so difficult to produce pions due to the recent improvements on particle accelerator science.

Charge kaons are still more difficult for the industrial applications to be obtained by the conventional techniques, because the invariant mass is larger than that of pions, and more than 1.5 GeV primary particles are required. But there is a possibility to achieve that in the nearest future by the high-intensity laser techniques now under development.

3. ELECTRIC FIELD REQUIREMENTS FOR MESON ACCELERATION

The lifetime of mesons is short, so the life-extension by the effect of the relativity and high-energy acceleration is required. The theoretical requirements are confirmed here by estimating the elongation of the time by solving the kinetic equation for the simple model including the relativity effect.

The kinetic equation in one-dimension can be described as follows:

$$\frac{dp}{dt} = qE \ , \tag{6}$$

$$p \equiv m_0 \gamma \upsilon \tag{7}$$

where p is the momentum of meson, t is the time in experimental system, q is the charge of meson, E is the external averaged electric field, m_0 is the invariant mass of meson, γ is the Lorentz factor of meson, υ is the velocity of meson, c is the light velocity in vacuum, and K is the kinetic energy of meson.

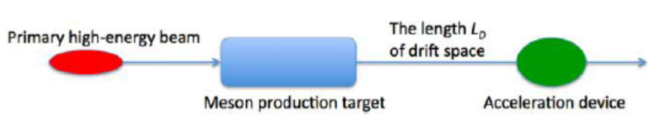

Figure 1: Simple model for the estimation of lifetime elongation.

Suppose that meson moves from the meson production target to the acceleration device at the initial velocity υ_0, and the Lorentz factor γ_0, and is accelerated by the averaged electric field E by the acceleration device with the length of a.

$$\beta\gamma = \beta_0\gamma_0 + \frac{qE}{m_0 c}t \tag{8}$$

$$\gamma = \sqrt{1 + (\beta_0\gamma_0 + \frac{qE}{m_0 c}t)^2} \tag{9}$$

The elongated time T_a is obtained as follows:

$$T_a = \frac{m_0 c}{qE}\{\sqrt{(\frac{qEa}{m_0 c^2} + \gamma_0)^2 - 1} - \beta_0\gamma_0\} \ . \tag{10}$$

The total time for meson T is written as follows:

$$T = \frac{L_D}{\gamma_0\beta_0 c} + \int_0^{T_a}\frac{1}{\gamma}dt \ . \tag{11}$$

Inserting eqs. (9) into eq. (11), we obtain the time for meson.

$$T = \frac{L_D}{\gamma_0\beta_0 c} + \frac{m_0 c}{qE}\ln[\frac{\gamma(1+\beta)}{\gamma_0(1+\beta_0)}] \tag{12}$$

The ratio of life extension can be estimated as follows:

$$\begin{aligned}
\lambda \equiv \frac{T_a}{T} &= \frac{\sqrt{(\frac{qEa}{m_0 c^2} + \gamma_0)^2 - 1} - \beta_0\gamma_0}{\frac{qEL_D}{m_0\gamma_0 c^2\beta_0} + \ln[\frac{\gamma(1+\beta)}{\gamma_0(1+\beta_0)}]} \\
&= \frac{\beta\gamma - \beta_0\gamma_0}{\frac{qEL_D}{m_0\gamma_0 c^2\beta_0} + \ln[\frac{\gamma(1+\beta)}{\gamma_0(1+\beta_0)}]} \\
&= \frac{p - p_0}{\frac{qEL_D}{m_0 c^2 p_0} + \ln[\frac{p + \sqrt{p^2+1}}{p_0 + \sqrt{p_0{}^2+1}}]} \\
& p \equiv \beta\gamma ; p_0 \equiv \beta_0\gamma_0
\end{aligned} \tag{13}$$

The required external electric field E can be estimated by solving the following two-dimensional equation.

$$\begin{aligned}
&\{(\frac{q\lambda L_D}{m_0\gamma_0 c^2\beta_0})^2 - (\frac{qa}{m_0 c^2})^2\}E^2 \\
&+2[\frac{q\lambda L_D}{m_0\gamma_0 c^2\beta_0}\{\lambda\ln[\frac{\gamma(1+\beta)}{\gamma_0(1+\beta_0)}] + \beta_0\gamma_0\} \\
&-\frac{qa}{m_0 c^2}\gamma_0]E + (\lambda\ln[\frac{\gamma(1+\beta)}{\gamma_0(1+\beta_0)}] + \beta_0\gamma_0)^2 \\
&-\gamma_0{}^2 + 1 = 0
\end{aligned} \tag{14}$$

Figure **2** shows the representative calculation results for various cases of the external electric field of 10 m long after 1 m drift space. The electric field of the traditional rf system with frequency modulation is less than 100 kV/m. The field produced by the conventional rf system with a fixed frequency is 1ess than 100 MV/m. The field of the conventional laser is achieved up to 1 TV/m, although the effective field area is very narrow. The high-intensity laser enables 100 TV/m, theoretically. It is effective for low-energy particles, but it is not so effective for high-energy particles. Figures **3** and **4** show the results for 0.5 m and 2.0 m drift space, respectively. Those results are limited by the

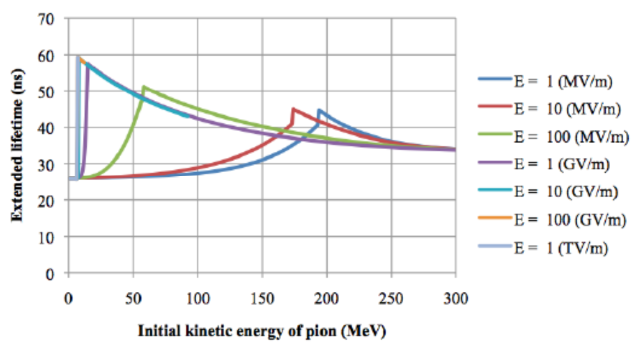

Figure 2: Lifetime extension of pions by each external electric field after 1 m drift space.

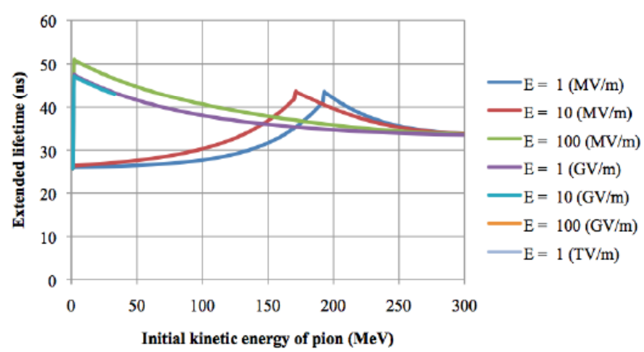

Figure 3: Lifetime extension of pions by each external electric field after 0.5 m drift space.

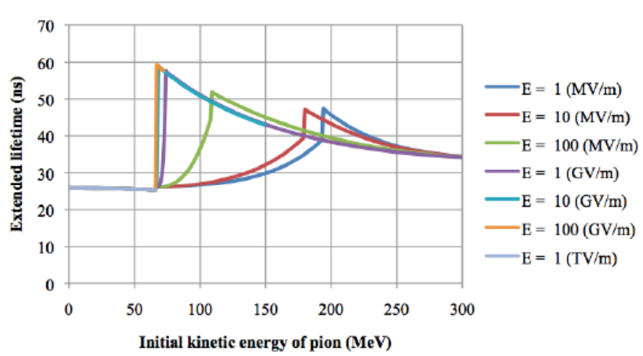

Figure 4: Lifetime extension of pions by each external electric field after 2 m drift space.

acceleration length of 10 m. The longer acceleration space enables longer lifetime extension, as shown in Figures. **5** and **6**, which show the results for 100 m and 1 km long of acceleration space, respectively.

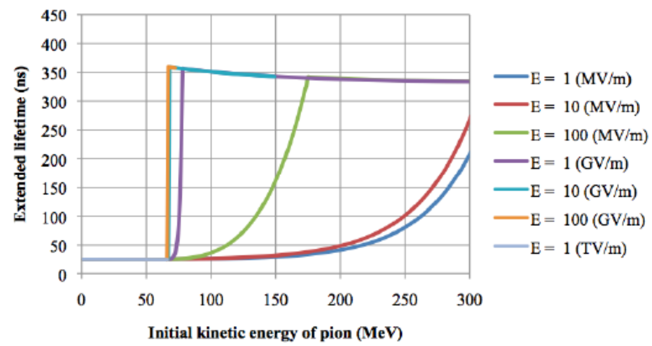

Figure 5: Lifetime extension of pions by each external electric field within 100 m long after 2 m drift space.

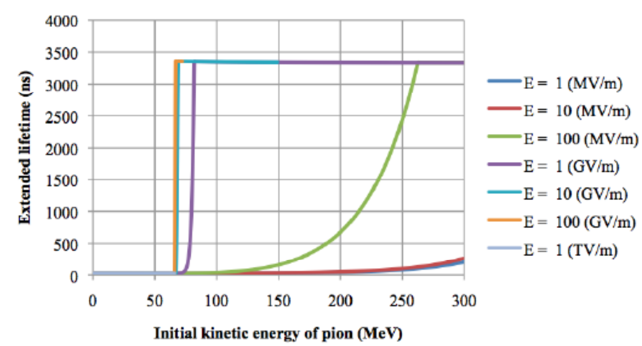

Figure 6: Lifetime extension of pions by each external electric field within 1 km long after 2 m drift space.

4. MAGNETIC FIELD REQUIREMENTS FOR MESON HANDLING

Mesons come out almost isotropic from the meson production target, so the focusing technique of mesons enables to improve the utility efficiency. A high gradient electric field is required especially for the lifetime extension. The effective area for such high electric field is limited, for example to 1 mm. The MegaGauss techniques have been developed recently, and are discussed for applications for meson focusing. The birth kinetic energy of mesons has a broad profile, and there are many low-energy mesons. 100 T solenoid field is enough for focusing (Figure **7**). The pre-acceleration by a high-intensity laser up to several times of initial energy is useful for the meson motion to be directional (Figure **8**).

SUMMARY

One of the possible scenarios of meson applications is presented by using electric field produced by high-

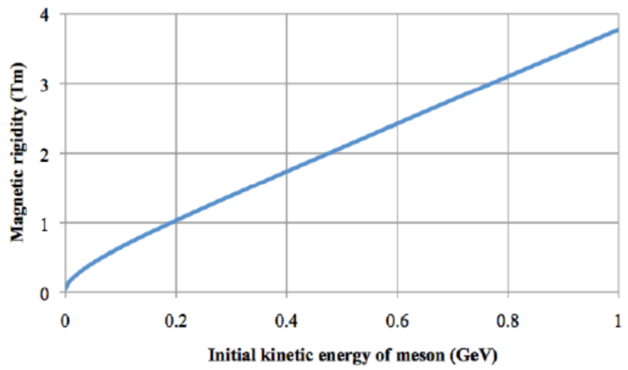

Figure 7: Magnetic rigidity of pion.

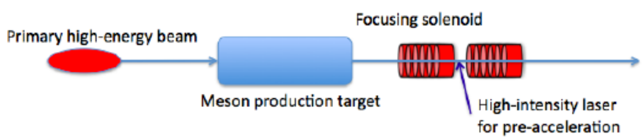

Figure 8: Schematic drawing of focusing and pre-acceleration.

gradient resonant cavities or laser for meson acceleration and magnetic field by the MegaGauss techniques for meson beam focusing. The requirements for fields are discussed to achieve the elongation of the short lifetime of mesons to μs. It is worth to discuss the practical meson applications, and optimization studies will be scheduled in the nearest future.

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